DTU Library

Topology optimization of reinforced concrete structures

Amir, Oded

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

Topology optimization of reinforced concrete structures

Oded Amir

Technical University of Denmark, Department of Mechanical Engineering, odam@mek.dtu.dk

Summary: Recent advances regarding topology optimization procedures of reinforced concrete structures are presented. We discuss several approaches to the challenging problem of optimizing the distribution of concrete and steel reinforcement. In particular, the consideration of complex nonlinear constitutive models in the context of topology optimization is addressed.

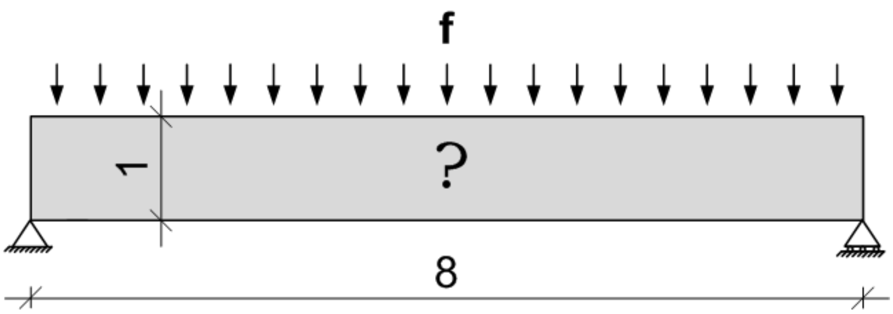
Introduction

Structural optimization techniques are becoming an integral part of the design process and are widely applied, for example, in the automotive and aerospace industries. On the other hand, optimal design had less impact on traditional structural engineering as practiced in the construction industry. The purpose of this study is to develop new topology optimization procedures that facilitate optimal design of reinforced concrete structures. The motivation comes from two main factors. First, the growing interest within the architectural community in utilizing structural optimization, and in particular topology optimization, for conceptual structural design [1, 2]. Second, the construction industry seeks more efficient designs in order to reduce CO_2 emissions associated with cement production for concrete construction.

Extended SIMP approach

The first approach implemented in this study is essentially an extension to the widely applied SIMP interpolation scheme [3]. Concrete and reinforcing steel are both considered as elasto-plastic materials, including appropriate yield criteria and post-yielding response. For this purpose, the Drucker-Prager and von Mises yield functions are utilized to represent the concrete and steel phases, respectively. Any mixture of the two candidate materials is represented using material interpolation rules for post-yielding behavior in addition to the standard interpolation of elastic properties. The resulting interpolation functions provide a nonlinear constitutive law as a function of the relative material density, which is the design variable as in standard topology optimization procedures. This approach can easily be generalized to accommodate other combinations of nonlinear materials besides steel and concrete (M. Bogomolny and O. Amir 2011, article in preparation).

The resulting optimized layouts demonstrate the potential of applying optimization tools in reinforced concrete design. When distributing steel within a concrete beam, the placement of reinforcement resembles traditional design and agrees with common engineering knowledge, meaning that steel replaces concrete in regions that undergo significant tensile stresses. One example is given in Figure 1. Despite several promising results, in some cases this formulation leads to the generation of layouts in which some of the concrete undergoes tensile stresses while some of the steel is used in compression. This was experienced when attempting to generate optimal strut-and-tie layouts, with concrete members in compression and steel members in tension. Possible reasons for this deficiency are: 1) The choice of objective function which aims at finding the stiffest design rather than at avoiding fracture in the concrete phase; and 2) The assumed elasto-plastic behavior that does not include strain-softening of the concrete. Further enhancement of this approach by replacing the rate-independent plasticity constitutive model by a plastic-damage model (e.g. [4]) is in the center of current research efforts.



(a) Design domain and boundary conditions.

(b) Optimized layout after 150 design iterations.

Figure 1: Topology optimization of a simply supported beam subject to a distributed load. The objective is to maximize the end-compliance under a prescribed displacement at the upper mid point. Black = steel, white = concrete. Steel consists of 10% of the total volume.

Homogenization approach

This contribution is expected to present also preliminary results obtained by a multi-scale procedure. Topology optimization is performed on the macro level, while on the micro level reinforced concrete is treated as an anisotropic composite material. The main challenge is obtaining the nonlinear constitutive properties of the composite micro-level material, since concrete is typically represented using a damage model with strain-softening and steel is considered elasto-plastic with strain-hardening. Furthermore, it may also be required to take into account complex interactions between the concrete matrix and the reinforcement, such as debonding (bond slip) and bending (dowel action) of the steel bars. The effective material properties of reinforced concrete can be evaluated by the homogenization method [5] or by averaging procedures [6]. In this approach, uni-directional and orthotropic reinforcement will be considered. This means there are three design variables for each material point: total material density; relative reinforcement density; and reinforcement angle.

References

[1] P. Dombernowsky and A. Søndergaard. Three-dimensional topology optimisation in architectural and structural design of concrete structures. In *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium*, Valencia, Spain, 2009.

[2] L. Frattari, R. Vadori, R. D'Aria, and G. Leoni. Topology optimization in architecture: may it be a design tool? In *Proceedings of the 8th World Congress on Structural and Multidisciplinary Optimization*, Lisbon, Portugal, 2009.

[3] M. P. Bendsøe. Optimal shape design as a material distribution problem. *Structural Optimization*, 1:193–202, 1989.

[4] J. Lubliner, J. Oliver, S. Oller, and E. Oñate. A plastic-damage model for concrete. *International Journal of Solids and Structures*, 25:299–326, 1989.

[5] E. Rumanus and G. Meschke. Homogenization-based modelling of reinforced concrete in the context of durability-oriented analyses. In *6th International Conference on Fracture Mechanics of Concrete and Concrete Structures*, Catania, Italy, 2007.

[6] S. Pietruszczak and A. Winnicki. Constitutive model for concrete with embedded sets of reinforcement. *ASCE Journal of Engineering Mechanics*, 129(7):725–738, 2003.